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A coupled ALE-Cohesive formulation for layered structural systems

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Abstract

A computational formulation able to simulate crack initiation and growth in layered structural systems is proposed. In order to identify the position of the onset interfacial defects and their dynamic debonding mechanisms, a moving mesh strategy, based on Arbitrary Lagrangian-Eulerian (ALE) approach, is combined with a cohesive interface methodology, in which weak based moving connections are implemented by using the finite element formulation. Contrarily to the existing models available from the literature, the proposed approach appears to be able to describe dynamic debonding processes with a relatively low number of computational elements also in specimens without a pre-existing interfacial crack. The numerical formulation has been implemented by means separate steps, concerned, at first, to identify the correct position of the onset cracks and, subsequently, their growth by changing the computational geometry of the interfaces. In order to verify the accuracy and to validate the proposed methodology, comparisons with experimental and numerical results are developed. In particular, the results, in terms of location and speed of the debonding front, obtained by the proposed model, are compared with the ones arising from the literature. Moreover, a parametric study in terms of geometrical characteristics of the layered structure are developed. The investigation reveals the impact of the stiffening of the reinforced strip and of adhesive thickness on the dynamic debonding mechanisms.

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Keywords: debonding; ALE; dynamic delamination; FEM; crack onset; layered structures.

1. Introduction

During the last decades, layered structures in the form of laminates or thin films have employed extensively in many engineering fields, ranging from nano to macro scale applications. Typically, such materials are formed by strong layers and weak interfaces, in which internal material discontinuities may evolve, producing relevant loss of stiffness (Barbero (2010)). Moreover, the crack evolution is strongly affected by the time rate of the external loading,

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which typically produces high amplifications of the fracture parameters. As a matter of fact, the measured crack tip speeds, during crack propagation, are relatively high, ranging also close to the Rayleigh wave speed of the material (Bruno et al. (2005); Greco and Lonetti (2009)). Therefore, in order to predict the interfacial crack growth, models developed also in a dynamic framework are much required.

In order to simulate debonding phenomena in layered structures, several approaches have been proposed in the literature. However, among the most important ones, Fracture Mechanics (FM) and Cohesive Zone Model (CZM) are widely utilized in practice (Rabinovitch (2008)). In FM, the total energy release rate and its individual mode components need to be evaluated, in order to predict delamination growth. For general configurations energy release rates can be computed by using a very accurate mesh of solid finite elements and the Virtual Crack Closure Method (VCCM) (Camacho and Ortiz (1996)). Such models calculate the energy release rate as the work performed by the internal traction forces at the crack faces during a virtual crack advance of the tip. Moreover, in dynamic Fracture Mechanics, the VCCM is applied by using the modified form, in which the ERR, during the time evolution, is evaluated by the product between the reaction forces and the relative displacements at the crack tip and at the nodes closer to the crack tip front, respectively, (Bruno et al. (2005)). The prediction of the energy release rate is strictly dependent on the mesh discretization of the crack tip. However, the resulting model is affected by computational complexities, because of the high number of variables and nonlinearities involved along the interfaces. Contrarily, CZM are based on damage formulation making use of interface cohesive elements between each layers, reproducing material interfaces. In this framework, strain softening interface elements with a damaged constitutive relationship are introduced between the crack faces. Cohesive models represent an alternative way to take into account for dynamic crack propagation, since the crack growth is predicted by releasing interfacial constraints, which reproduce displacements continuity between cracked faces. In order to avoid such problems, combined formulations based on fracture and moving mesh methodologies are proposed (Funari et al. (2016)). In particular, the former is able to evaluate the variables, which govern the conditions concerning the crack initiation and growth, whereas the latter is utilized to simulate the evolution of the crack growth by means of ALE formulation (Bruno et al. (2013)). It is worth noting that the use of moving mesh method, combined with regularization and smoothing techniques, appears to be quite efficient to reproduce the evolution of moving discontinuities. However, existing models based on ALE and Fracture mechanics are based on a full coupling of the governing equations arising in both structural and ALE domain. In this framework, material and mesh points in the structural domain produce convective contributions and thus nonstandard terms in both inertial and internal forces. In the proposed formulation, the use of a weak discontinuity approach avoids the modification of the governing equations arising from the structural model and thus a lower complexity in the governing equations and the numerical computation is expected. Despite exiting numerical methodologies based on pure CZM, the present approach reduces the nonlinearities involved in the governing equations to a small region containing the process zone, leading to a quite stable and efficient procedure to identify the actual solution in terms of both crack initiation and evolution. In order to verify the consistency of the proposed model, comparisons with existing formulations for several cases involving single and multiple delaminations are developed.

The outline of the paper is as follows. Section 2 presents the theoretical and the numerical aspect of the implementation, in which crack initiation and evolution conditions are discussed. In Section 3, numerical comparisons with existing formulations are proposed and a parametric study is carried out to investigate the dynamic characteristics of the debonding phenomena.

2. Theoretical and numerical implementation

The proposed model is presented in the framework of the layered structures, in which thin layers are connected through adhesive elements. The theoretical formulation is based on a multilayered shear deformable beam and a moving interface approach (Fig.1). The former is able to reproduce 2D solution by introducing a low number of finite elements along the thickness of the structure, whereas the latter is able to simulate the crack tip motion on the basis of the adopted growth criterion (Bruno et al. (2008)).

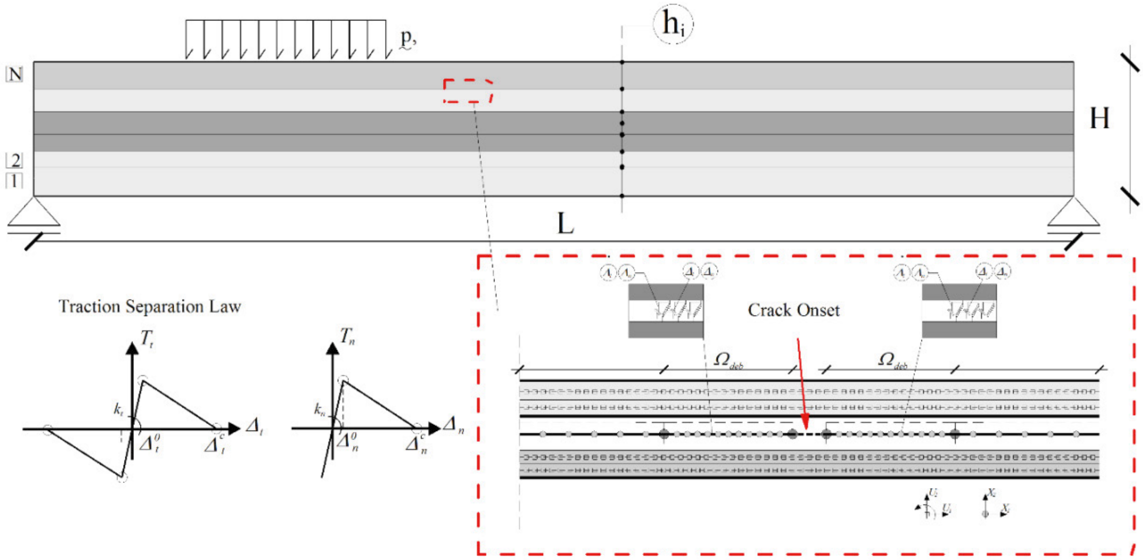


Fig. 1. Multilayered laminate structure: general representations of geometry, interface and TSL.

The mathematical description of the moving mesh modeling is defined by a mapping operator, which relies a particle in a fixed Referential Frame and the one in current material coordinate system. The mesh motion in terms of displacement field, at the k-th interface, is described as the difference between material X_1^k and the referential coordinates (ξ):

$$\Delta X_1^k = X_1^k(t) - \xi^k(t) = \Phi^k(\xi,t) - \xi^k(t) \qquad on \quad \Omega^k \tag{1}$$

where $\Omega^k = B \times h^k$ represent the region in which the debonding mechanisms are produced. In order to reduce mesh distortions, produced by the mesh movements, rezoning or smoothing equations are introduced to simulate the grid motion consistently to Laplace based equation which is, in the case of one dimensional domain for both Static (S) and Dynamic (D) cases, defined on the basis of the following relationships (Lonetti (2010)):

$$\Delta X^k_{,\xi\xi} = \frac{\partial^2 \Phi^k(\xi,t)}{\partial \xi^2}, \quad \Delta \dot{X}^k_{,rr} = \frac{\partial^3 \Phi^k(\xi,t)}{\partial t \partial \xi^2} \tag{2}$$

The crack onset definition is described by means of a mixed crack growth, which is a function of the fracture variables, coinciding with the ratio between ERR mode components and corresponding critical values, as follows:

$$g_T^k\left(X_1^k\right) = \left(\frac{G_I\left(X_1^k\right)}{G_{IC}}\right)^{\frac{r}{2}} + \left(\frac{G_{II}\left(X_1^k\right)}{G_{IIC}}\right)^{\frac{r}{2}} - 1 \tag{3}$$

where *k* represents the generic *k*-th interface in which debonding phenomena may occur, *r* is the constant utilized to describe fracture in different material and (G_{IC}, G_{IIC}) are the total area under the traction separation law, whereas (G_I, G_{II}) are the individual energy release rates calculated as $G_I = \int_0^{\Delta_n^c} T_n(\Delta_n)\, d\Delta_n$ and $G_{II} = \int_0^{\Delta_t^c} T_t(\Delta_t)\, d\Delta_t$. For each mode components, the Traction Separation Law (TSL) is assumed to be described by the critical cohesive stresses, $\left(T_t^c, T_n^c\right)$, the critical and initial opening or transverse relative displacements, namely $\left(\Delta_n^0, \Delta_n^c\right)$ and $\left(\Delta_t^0, \Delta_t^c\right)$. The numerical implementation of the proposed model is developed by using a finite element approach, in which the layered structure is modelled by the combination of shear deformable beam elements connected through the moving mesh interfaces. A Lagrange cubic approximation is adopted to describe both displacement and rotation fields, whereas linear interpolation functions are adopted for the axial displacements. Moreover, for the variables concerning moving mesh equations, quadratic interpolation functions are assumed to describe the mesh position of the computational nodes. The proposed approach takes the form of a set of nonlinear differential equations, whose solution is obtained by using a customized version of the finite element package Comsol Multiphysics combined with MATLAB script files (COMSOL (2014)). The model can be solved in both static and dynamic framework, taking into account the time dependent effects produced by the inertial characteristics of the structure and the boundary motion involved by debonding phenomena. In both cases, since the governing equations are essentially nonlinear, an incremental-iterative procedure is needed to evaluate the solution (Funari et al. (2016)). In the case of static analysis, the resulting equations are solved by using a nonlinear methodology based on Newton-Raphson or Arch length integration procedures. In the framework of a dynamic analysis, the algebraic equations are solved by using an implicit time integration scheme based on a variable step-size backward differentiation formula (BDF).

3. Results

In this section, results are developed with the purpose to verify the consistency and the reliability of the proposed model. At first, a layered structured formed by four mathematical layers and three intact interfaces are investigated in static framework. The main aim of the present analysis is to validate the proposed procedure to predict the onset conditions and the crack growth for a case involving multiple debonding mechanisms. Subsequently in order to validate the procedure to describe the crack front speed, the dynamic debonding mechanisms produced on a steel beam specimen have been investigated by means comparisons with numerical results arising from the literature.

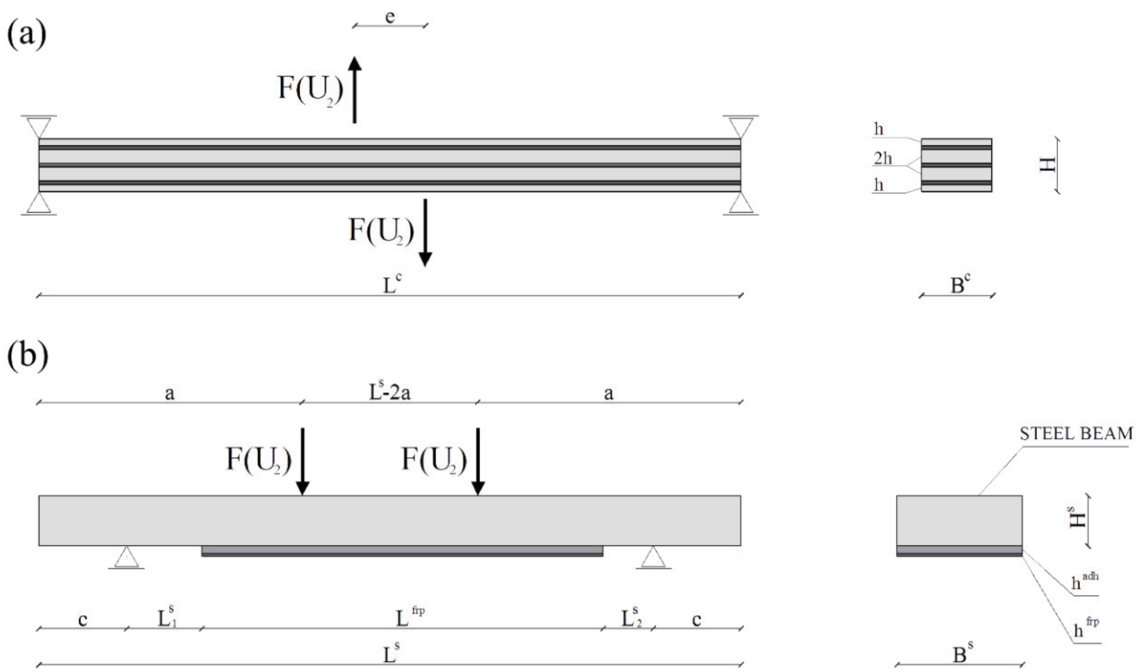


Fig. 2. (a) Laminate configuration and loading scheme; (b) Steel beam configuration and loading scheme.

Table 1. Geometrical, mechanical and interface properties of the laminate.

E_1 [GPa]	G_{12} [GPa]	L^c [mm]	B^c [mm]	h [mm]	H [mm]	e [mm]	ρ [Kg/mc]
130	6	200	20	2	12	20	1500
G_{IC} [N/mm]	T_n^c [MPa]	Δ_n^0 [mm]	Δ_n^c [mm]	G_{IIC} [N/mm]	T_t^c [MPa]	Δ_t^0 [mm]	Δ_t^c [mm]
0.26	30	0.00173	0.0173	1.02	60	0.00334	0.0334

Table 2. Geometrical, mechanical and interface properties of the steel specimen.

E_1^s [GPa]	G_{12}^s [GPa]	L^s [mm]	L_1^s [mm]	L_2^s [mm]	c [mm]	a [mm]	B^s [mm]	H^s [mm]	ρ^s [Kg/mc]
190	79.3	280	30	20	35	105	50	20	7500
E_1^{adh} [GPa]	G_{12}^{adh} [GPa]	L^{adh} [mm]	B^{adh} [mm]	h^{adh} [mm]	ρ^{adh} [Kg/mc]	ϕ^{ab} [N/mm]	δ_n^{ab} [mm]	-	-
5	0.350	160	50	3	2000	0.350	0.01	-	-
E_1^{frp} [GPa]	G_{12}^{frp} [GPa]	L^{frp} [mm]	B^{frp} [mm]	h^{frp} [mm]	ρ^{frp} [Kg/mc]	ϕ^{af} [N/mm]	δ_n^{af} [mm]	-	-
165	60	160	50	1.2	2000	0.350	0.01	-	-

3.1. Layered Structure – Multiple debonding mechanisms

The loading scheme, reported in Fig. 2a, is based on clamped end conditions and concentrated untisymmetric opening forces. Moreover, the mechanical properties assumed for the laminate and the interfaces as well as the ones required by the cohesive zone constitutive model are reported in Tab.1. The numerical model is discretized along the thickness by using one mathematical layer for each sublaminate, whereas, for the interfaces, three ALE elements are introduced between the sublayers, in which the crack initiation could be potentially activated.

The analysis is developed under a displacement control mode, to ensure a stable crack propagation. In order to verify the stability and accuracy of the solution, several mesh discretizations, ranging from a coarse uniform distribution to a refined one, are considered. In particular, for the proposed model, the following numerical cases are analyzed:

- uniform discretization of the mesh with a characteristic element mesh equal ΔD/L=2/200 (M1) with 1841 DOFs;
- uniform discretization of the mesh with a characteristic element mesh equal ΔD/L=1/200 (M2) with 3633 DOFs;

In addition, in order to verify the consistency of the proposed approach, a model based on Pure Cohesive approach, namely PC1, in which a uniform discretization of the mesh with a length equal ΔD/L=0.2/200 involving in 12012 DOFs is adopted. In Fig. 3a, results in terms of resistance curve are reported. The loading curve obtained by the proposed model is in agreement with the results obtained by using refined CZM approach. Moreover, in the case of a very low mesh element number (M1), the prediction in terms of resistance curve is not affected by a divergent behavior, but it is always very close to enriched one, namely PC1. In Fig. 3b, the evolution between crack tip and applied displacements for two different mesh discretizations are considered. The results show that the proposed model is quite stable, since the predictions in terms of crack tip displacements coincide with that of the PC1 solution. However, it should be noted that in the case of a pure cohesive approach, the crack tip position is taken as the point where the fracture function of the cohesive interface tends to zero, whereas, in the proposed model, an explicit movement of ALE region is identified, since it corresponds to a variable which enters in the computation.

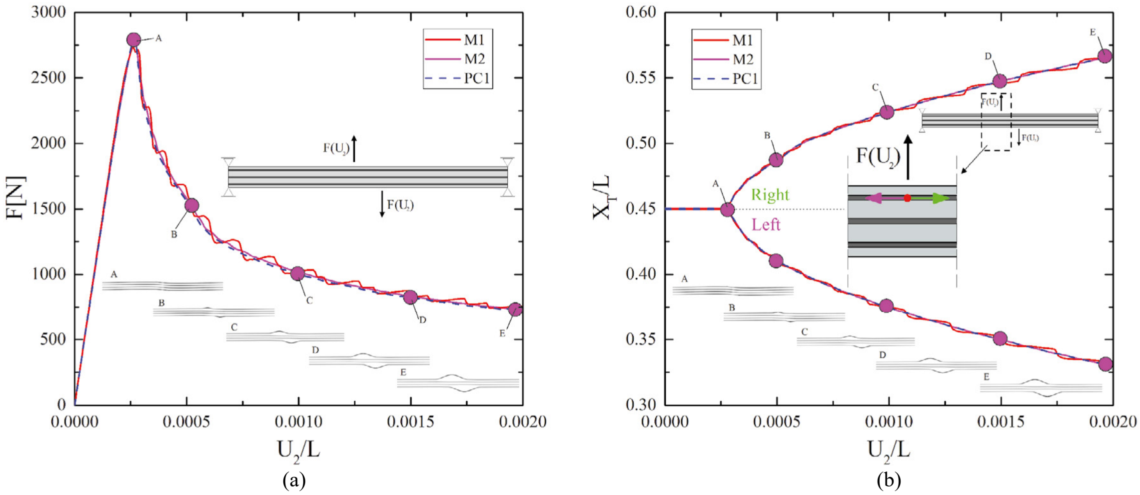


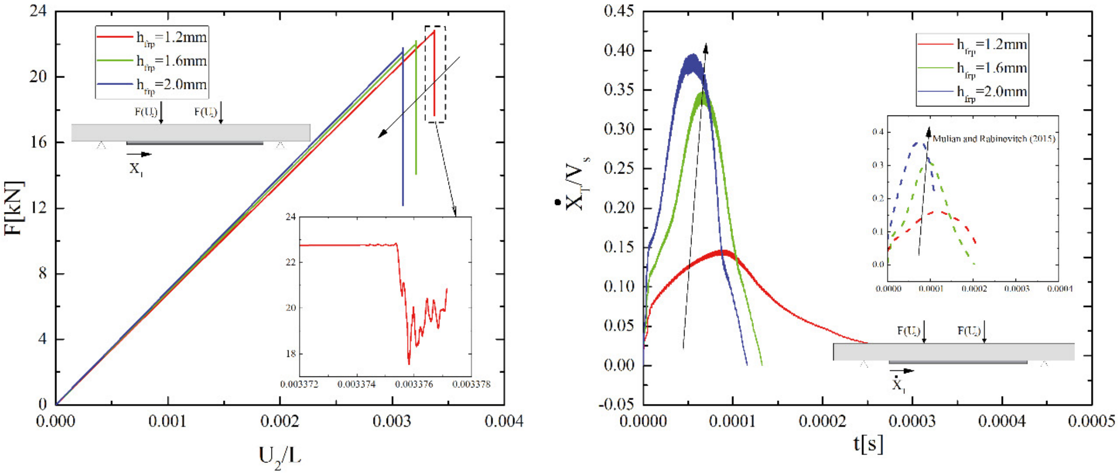
Fig. 3. Comparisons in terms of loading curve (F-U_2/L) with pure cohesive approach (a); Comparisons in terms of cracks tip position (X_T-U_2/L) with pure cohesive approach.

3.2. FRP strengthened steel beam specimen

The analyses are developed with reference to loading schemes based on the 4-point bending, in which the dynamics effects are considered from both onset and evolution mechanisms. The loading, the boundary conditions and the geometry are illustrated in in Fig. 2b, whereas the mechanical properties assumed for the laminate and the interfaces as well as the ones required by the potential cohesive zone model are reported in Tab.2. In the present study, comparisons with results arising from the literature (Mulian and Rabinovitch (2015)) are developed. The main model refers to a steel beam, strengthened with FRP strip elements. The model is based on two cohesive interface elements, which are introduced between adhesive-steel and adhesive-FRP strip elements. As a consequence, debonding phenomena may affect the layered structures at two different interface levels. The interface law utilized to reproduce the debonding process is consistent with the model proposed by (Volokh and Needleman (2002)).

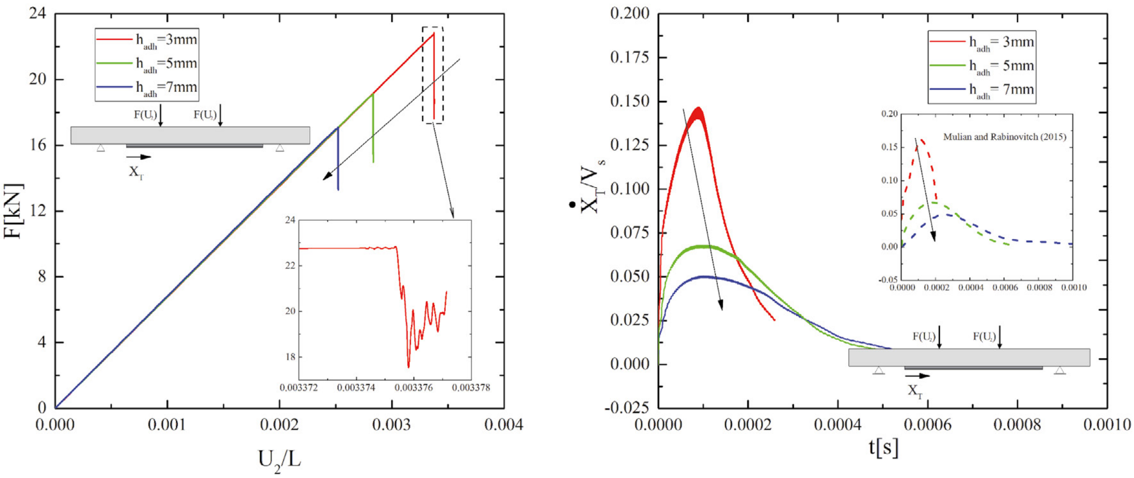
In order to obtain a stable crack propagation, the structure is loaded under a displacement control mode. In particular, to avoid the dynamic effects due to the external load, a very small loading rate equal to 1 mm/s is assumed. However, time steps are modified during the computation from 1E-3s to 1E-7s before and after the activation of the debonding phenomena, to capture accurately the effects produced by crack growth.

In Fig. 4, results in terms of resistance curve and crack speed time histories for different thickness of the FRP strips are reported. At first, the structure reveals a linear, stable and quasi-static behavior. Subsequently, when the crack growth criterion is satisfied in the adhesive-steel interface, the ALE interface is activated to reproduce the debonding phenomena. During the activation of debonding mechanisms, the resistance curve presents an oscillatory and variable behavior which varies very fast. However, in the same figure, a details of the resistance curve at the point in which the crack onset is activated is also reported. This trend is quite in agreement with similar experimental results available from the literature (Lundsgaard-Larsen et al. (2012)), which show the dominant dynamic effects of the crack growth. It is worth nothing that the resistance curves are quite dependent from the thickness properties of FRP strip. In particular, the increase of the FRP strip thickness reveals a similar impact on the critical displacement and load at the onset of the dynamic process (Fig. 4). Increasing the thickness of the FRP strip, the edge debonding strength of the beam is reduced (Fig. 4a). This effect is attributed to the increased amount of energy that is accumulated in the stiffened FRP layer and the corresponding increase of the edge stresses. Once the dynamic process is started, the influence of the FRP strip thickness produces an increase of the crack speeds, which leads to more severe failure mechanisms. Contrarily, to the properties of the FRP layer, which are commonly well controlled and well documented by the manufacturer of the composite material, the geometric properties of the adhesive are now investigated (Mulian and Rabinovitch (2015)). To this end, in Fig 5, results in terms of resistance curve and crack speed time histories for different value of the thickness of the adhesive layer are presented. In particular, an increase of the thickness of the adhesive layer reveals a different impact with respect the previous analyses reported in Fig. 4. As a matter of fact, the results show how by using thin adhesive layers an increase of the dynamic debonding strength is observed (Fig. 5a) leading the structure to a more severe dynamic state (Fig. 5b). In both analyzed cases, the results reported in Fig. 4 and 5 are in good agreement with the data available from the literature (Mulian and Rabinovitch (2015)). Finally, the consistency of the proposed model has been investigated also in terms of computational efforts. In particular, in order to satisfy the solution accuracy, the numerical model arising from (Mulian and Rabinovitch (2015)) is based on the discretization of 560 equal lengths for the concrete layer, 320 to FRP strip layer, whereas to discretized the 2D adhesive layer, a uniform length equal to 0.5 was used. As a consequence, the total number of DOFs is approximately 7100. Contrarily, by using the proposed approach, in which also the adhesive layer is simulated by means the shear deformable beam elements, the number of variables is strongly reduced. In particular, the proposed model has been discretized by means a uniform mesh length equal to 1 mm for the laminate, and 1 mm for the interface involving in 3018 DOFs. Therefore, a computational saving approximately equal to 60% is achieved.



(a) (b)

Fig. 4. Comparisons in terms of loading curve (F-U_2/L) for different thickness of the FRP strip(a); Comparisons in terms of time histories of the debonding front speed for different thickness of the FRP strip (b).



(a) (b)

Fig. 5. Comparisons in terms of loading curve (F-U_2/L) for different thickness of the adhesive layer (a); Comparisons in terms of time histories of the debonding front speed for different thickness of the adhesive layer (b).

Conclusions

The proposed model is developed with the purpose to study the delamination processes in layered structures. Compared with existing formulations available from literature, this model presents lower computational efforts and complexities in the governing equations. In particular, the model presented in (Funari et al. (2016); Funari et al. (2016)) has been extended and reviewed with the purpose to identify also crack onset mechanisms. In order to validate the proposed model comparisons with numerical results obtained by pure cohesive approach are reported. Finally, some parametric studies have been developed in terms of geometric characteristics of the layered structures for FRP strengthened steel beams, which reveals a good agreement with existing results available in literature.

References

Barbero, E., 2010. Introduction to Composite Materials Design. CRC Press.

Bruno, D., Greco, F., Lonetti, P., 2005. A 3D delamination modelling technique based on plate and interface theories for laminated structures. European Journal of Mechanics a-Solids, 24, 127-149.

Bruno, D., Greco, F., Lonetti, P., 2005. Computation of energy release rate and mode separation in delaminated composite plates by using plate and interface variables. Mechanics of Advanced Materials and Structures, 12, 285-304.

Bruno, D., Greco, F., Lonetti, P., Nevone Blasi, P., 2008. Influence of micro-cracking and contact on the effective properties of composite materials. Simulation Modelling Practice and Theory, 16(8), 851-884.

Bruno, D., Greco, F., Lonetti, P., 2013. A fracture-ALE formulation to predict dynamic debonding in FRP strengthened concrete beams. Composites Part B-Engineering, 46, 46-60.

Camacho, G.T., Ortiz, M., 1996. Computational modelling of impact damage in brittle materials. International Journal of Solids and Structures, 33(20-22), 2899-2938.

COMSOL Multiphysics reference guide. 2014.

Funari, M.F., Greco, F., Lonetti, P., 2016. A moving interface finite element formulation for layered structures. Composites Part B-Engineering, 96, 325-337.

Funari, M.F., Greco, F., Lonetti, P., 2016. A cohesive finite element model based ALE formulation for z-pins reinforced multilayered composite beams. Procedia Structural Integrity 2, 452-459.

Greco, F., Lonetti, P., 2009. Mixed mode dynamic delamination in fiber reinforced composites. Composites Part B-Engineering, 40(5), 379-392.

Greco, F., Leonetti, L., Lonetti, P., 2015. A novel approach based on ALE and delamination fracture mechanics for multilayered composite beams. Composites Part B-Engineering, 78, 447-458.

Lonetti, P., 2010. Dynamic propagation phenomena of multiple delaminations in composite structures. Computational Materials Science, 48 (3), 563-575.

Lundsgaard-Larsen, C., Massabo, R., Cox, B.N., 2012. On acquiring data for large-scale crack bridging at high strain rates. Journal of Composite Materials 46(8), 949-971.

Mulian, G., Rabinovitch, O., 2015. Debonding dynamics in FRP plated beams: high order cohesive FE formulation and parametric sensitivity, International Journal of Fracture, 195, 53-78.

Rabinovitch, O., 2008. Cohesive interface modeling of debonding failure in FRP strengthened beams. Journal of Engineering Mechanics-Asce 134(7), 578-588.

Volokh, K. Yu., and Needleman, A., 2002. Buckling of sandwich beams with compliant interfaces. Computers and Structures 80, 1329–1335.